SUPPLEMENTARY INFORMATION: Additive interfacial chiral interaction in multilayers for stabilization of small individual skyrmions at room temperature

Description of the magnetic imaging technique As mentioned in the Method section, we have performed the scanning transmission x-ray experiments on two different beamlines: X07DA (PolLux) beamline at the Swiss Light Source, Paul Scherrer Institute, Villigen, Switzerland, and the Maxymus beamline, BESSY II, Adlershof, Germany. The images were recorded by scanning the multilayers grown on Si_3N_4 membranes with an x-ray beam focused by a Fresnel zone plate, providing a resolution down to 30 nm. Circular polarized light with normal incidence is used to map the out-of-plane magnetization using the x-ray Magnetic Circular Dichroism (XMCD) effect (see Fig. S1). For imaging, we scan the samples at the Co L_3-edge (corresponding to the 2*p*-3*d* transitions) at 779.95 eV. In order to get some quantitative information about the DMI, we analyze the evolution of skyrmion dimensions with $H_\perp$. Assuming that the intensity of the circularly polarized x-ray beam going through a layer is given by $I = I_0 \exp(-\mu\, t)$, where I_0 is the intensity of the incoming light, μ the absorption and t the thickness of the layer, it can be demonstrated that the quantity $\mu_p - \mu_m$ (index m and p for the different helicities) is proportional to the out-of-plane magnetization m_z. This remains true even in the case of an x-ray beam that is not 100% circularly polarized or if the positive helicity has not the same polarization level than the negative one (because we also scanned areas of membrane without magnetic material for the normalization). Therefore, all the experimental maps of the magnetic configurations (see for example Fig. 1b-e) presented in this work are obtained by calculating the maps of the absorption difference $\mu_p - \mu_m$. Imaging of smaller magnetic disks is also presented in Fig. S2.

Determination of skyrmion diameter from STXM images

The actual diameter of the circular-shape domains is found to be often smaller than the actual dimension of the polarized x-ray beam. In fact, in the presented STXM experiments, the full width at half maximum (FWHM) of the beam was either 45 or 91 nm depending on the beamline and the experimental conditions (aperture slits, divergence, zone plate). However assuming a typical circular shape of the magnetic skyrmions and convoluting it with a Gaussian x-ray beam profile, it is then possible to fit the experimental images and thus deduce the actual skyrmion diameters down to 20 nm (see Fig. S3). More precisely, the assumed magnetization profiles are corresponding to approximated circular skyrmions for which the magnetization m is rotating continuously with the distance from skyrmion center r, *i.e.* $m_z(r) = \cos(\pi r/(2r_S))$ for $r < 2r_S$.[1] To improve the signal/noise ratio, we average over a few lines, typically corresponding to the beam FWHM. The skyrmion profiles are then compared to the ones determined in micromagnetic simulations including DMI. In Fig. S3, we illustrate such image analysis and comparison to ideal profiles for two different perpendicular applied magnetic fields for the Pt|Co|Pt multilayers.
in the Co layers but is obtained by considering that one atomic plane of Pt and Ir is magnetized. A magnetization at saturation of around 1/5 of the one of Co was observed in Pt/Co multilayers.[2]

Quantitative estimation of DMI and role of proximity induced moment of the heavy atoms, simulation details

As presented in the main text, we have used two different methodologies to extract the DM amplitude from the analysis of the STXM images *i.e*. the evolution of skyrmion diameter with $H_\perp$ (see Fig. 2), and the evolution with the DMI of the mean domain width at zero applied field (see Fig. 3). For this latter approach, the domain periodicity (twice the single domain size) at remanence as shown in Fig. 3 are obtained by Fourier transform. The remnant domain structure observed in Pt|Co|Pt films (with large lithographic structures) is shown in Fig. S4. The quantitative estimation of the DMI amplitude is obtained by comparison with micromagnetic simulations including the interfacial DM energy. In order to perform these simulations, we have to introduce input material parameters that are the saturation magnetization M_s and the magnetic out-of-plane uniaxial anisotropy K. Moreover, the dipole interactions are also taken into account. We checked that, with our material properties, topologically "trivial" bubbles (winding number equal to zero) stabilized by dipolar interaction only, vanish under magnetic field ($\approx$ 50 mT or more) or turn into skyrmions (winding number equal to one) if finite DMI amplitude is introduced ($\geq$ 1 mJ/m^2 for the typical parameters). Using our experimental determination of the saturation magnetization and the perpendicular anisotropy of the multilayers, two hypotheses can be considered. The first series of simulations (presented in the main text) have been performed under the assumption that the total experimental measured magnetization and total experimental anisotropy energy of the multilayer is concentrated in ten 0.6 nm-thick Co layers having the stiffness constant of cobalt and separated by 2 nm-thick vacuum layers. Consistently the effective magnetization of Co is simply obtained by dividing the total magnetization by the total Co thickness, *i.e.* 6.6 nm. The effective anisotropy constant is deduced from the saturation field measured in the in-plane magnetic hysteresis curve. As presented in the main text and reproduced in Fig. S5, the best agreement between experimental data and simulations is obtained for D = 1.9 ± 0.2 mJ/m^2. In a second series of simulations presented here, we have considered the case of that the interfacial Pt and Ir atomic layers can acquire a small magnetic moment by proximity effect with the Co layers. In this case, the experimental magnetization (and the effective anisotropy thereof) is no more fully concentrated in the Co layers but is obtained by considering that one atomic plane of Pt and Ir is magnetized. A magnetization at saturation of around 1/5 of the one of Co was observed in Pt/Co multilayers.[2] Note that the maximum possible value of the interlayer electronic coupling between two of these (Pt 0.2nm|Co 0.6nm|Ir 0.2nm) magnetic layers across a 1.6nm thick nonmagnetic Pt/Ir bilayer can be estimated by considering the record values found by Bloemen *et al.*[3] with Ru spacers between Co, approximately J = 0.2 and J = 0.1 mJ/m^2 for respectively 1.1 nm (ferromagnetic coupling peak) and 1.8 nm (antiferromagnetic peak). These couplings are equivalent to a coupling by an interlayer magnetic material having a stiffness constant $A = 2Jt/\pi^2$ smaller than A in Co by three orders of magnitude. They are much too small to affect the internal spin configuration of the skyrmions and, in consequence, can be neglected in the simulation of this spin configuration. However the electronic interlayer coupling may help the dipole interaction for the coupling of the magnetic textures from the top to the bottom of the multilayer.

As shown in Fig. S5, this second case leads to a slightly different estimation of the DMI amplitude from the evolution of the skyrmion diameter with field with a value equal to D = 1.4±0.2 mJ/m^2 for the Ir|Co|Pt multilayer.

References: 1. Kiselev, N. S., Bogdanov, A. N., Schäfer, R. & Rößler, U. K. Chiral skyrmions in thin magnetic films: new objects for magnetic storage technologies? *J. Phys. D: Appl. Phys.* 44, 392001 (2011). 2. Grange, W., Maret, M., Kappler, J.-P., Vogel, J., Fontaine, A., Petroff, F., Krill, G., Rogalev, A., Goulon J., Finazzi, M., Brookes, N. B., Magnetocrystalline anisotropy in (111) $CoPt_3$ thin films probed by x-ray magnetic circular dichroism. *Phys. Rev. B* **58**, 6298-6304 (1998) 3. Bloemen, P. J. H., van Kesteren, H. W., Swagten, H. J. M., de Jonge, W. J. M., Oscillatory interlayer exchange coupling in Co/Ru multilayers and bilayers. *Phys. Rev. B* **50**, 13505 (1994).

Supplementary Figures:

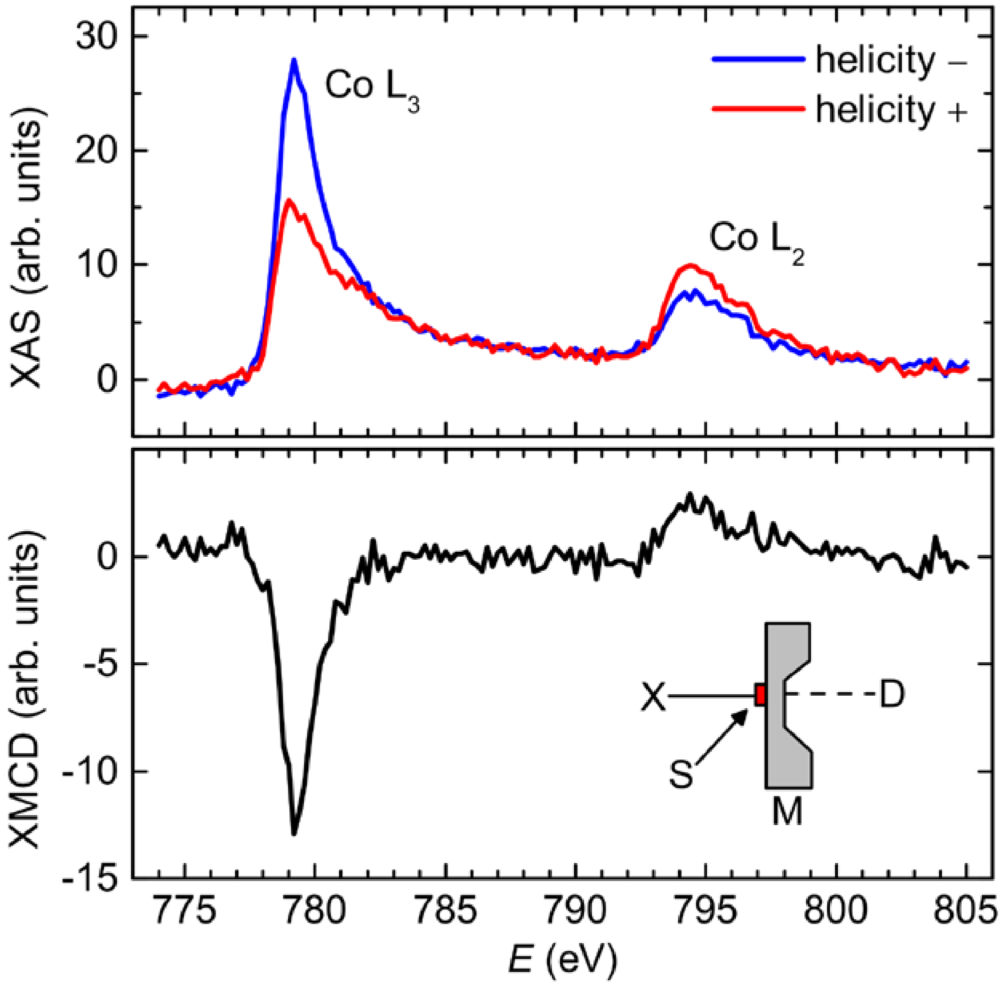

Fig. S1. XAS of the $L_{3,2}$ peaks of Co and the corresponding XMCD obtained on $\{Co0.6|Pt1\}_{10}$ at the PolLux beamline. The XAS were obtained by normalizing the intensity by the intensity of the nearby membrane and then offset to bring the pre-edge value to zero. XMCD is obtained from the difference of these XAS. The inset shows a very schematic cut diagram of the incoming x-ray beam (X), the sample (S) on top of the membrane (M), and the photon counter (D).

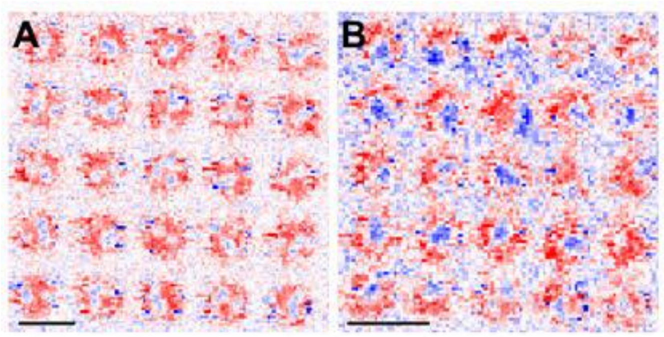

Fig. S2. Image of 300 (**A**) and 200 nm-diameter (**B**) disks. The scale bars are 500 nm.

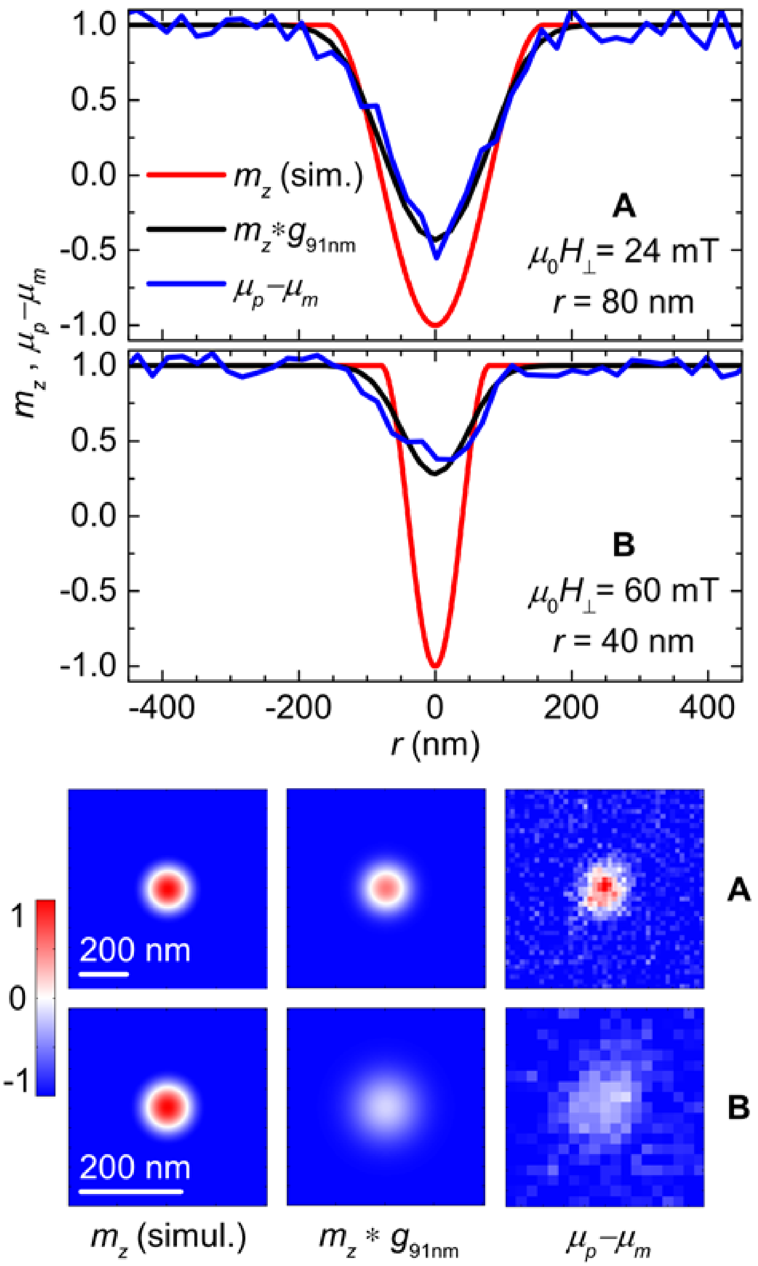

Fig. S3. Magnetization profile of skyrmions: Cross section of a skyrmion recorded in the Pt|Co|Pt multilayer obtained for $\mu_0 H_\perp$ = 24mT (**A**) and $\mu_0 H_\perp$ = 60mT (**B**). We plot the expected skyrmion magnetic profile (red curves, m_z), this ideal profile is convoluted with a 2D-Gaussian of FWHM of 91 nm averaged over four lines (black curves, $m_z * g_{91nm}$), and the actual profile also average over four lines (blue curves, μ_p-μ_m). The corresponding magnetization maps are displayed in the bottom, the right-most being experimental data.

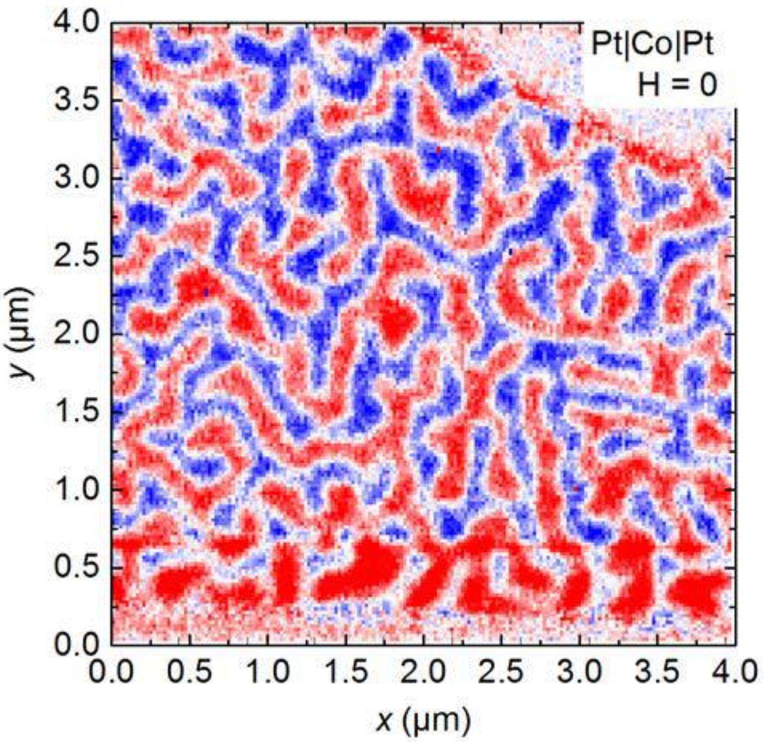

Fig. S4. Domain structure of the Pt|Co|Pt samples at remanence and room temperature.

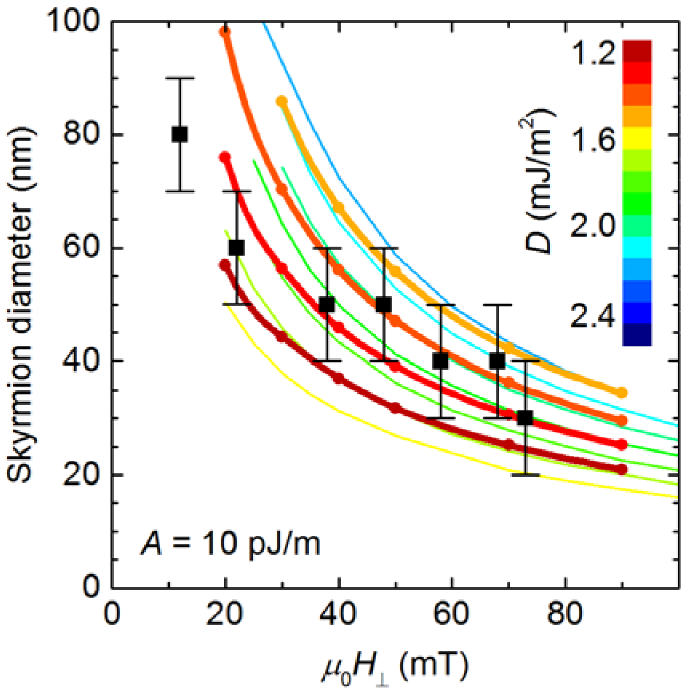

Fig. S5. Comparison of the skyrmion diameter in Ir|Co|Pt as a function of the external out-of-plane magnetic field $H_\perp$ for different values of the DMI amplitude *D*, in the case where small magnetic moments on Pt and Ir atoms due to proximity effect with Co layer are considered *i.e.* with a finite interlayer coupling (thick lines, see text for details). Thin lines correspond to simulations with the hypothesis explained in the main text and correspond to Fig. 2b.